

A Novel Scheme to Aid Coherent Detection of GMSK Signals in Fast Rayleigh Fading Channels

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Abstract.

A novel scheme to insert carrier pilot to GMSK signal using Binary Block Code (BBC) and a highpass filter in baseband is proposed. This allows the signal to be coherently demodulated even in a fast Rayleigh fading environment. As an illustrative example, the scheme is applied to a 16 kb/s GMSK signal, and its performance over a fast Rayleigh fading channel is investigated using computer simulation. This modem's "irreducible error rate" is found to be $P_e = 5.5 \times 10^{-5}$ which is more than one order of magnitude lower than that of differential detection. The modem's performance in Rician fading channel is currently under investigation.

1. Introduction.

GMSK [1] is a digital modulation with appealing characteristics for mobile communications. In slow fading channels, GMSK can be detected either coherently or non-coherently. In a fast fading channel environment however, accurate carrier recovery is difficult and non-coherent detection is preferred [15].

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A limiting factor in relatively low bit rate modem operation over fast Rayleigh fading channel is the "irreducible error rate". In coherent detection, this is caused by the deep fades that force the carrier recovery loop to hang up and lose synchronization even in the absence of channel noise [14]. In differential detection, it is caused by random FM noise that partially destroys the carrier phase coherency in adjacent symbol time. Theoretical and simulation studies [4] show that the irreducible error rate for a 16 kb/s GMSK system with $BT=0.25$ and 2T differential detection is approximately 10^{-3} when the Doppler frequency is $f_D=100\text{Hz}$ [4].

A useful technique to lower the "irreducible error rate" is to transmit an in-band pilot tone at the carrier frequency.

Provided that mutual interference with the data signal is avoided, the received pilot can be extracted using a simple bandpass filter to aid accurate coherent demodulation. The main drawbacks of pilot schemes are (1) the pilot takes up additional power and/or bandwidth, and (2) it destroys the otherwise constant envelope property of certain modulations. However, under some

circumstances, the benefit of coherent detection can outweigh these shortcomings. Some well-known examples are the Tone Calibrated Technique (TCT) [5] and the Transparent-Tone-In-Band (TTIB) technique [6].

In the literature, there are reports on in-band carrier pilot insertion for linear modulations such as BPSK [7], MPSK[8], QPRS[9], and QAM[10]. But there appears to be little study on its application to non-linear modulation. In this paper, we address the issue by extending the technique to GMSK. We propose a modified modem structure which allows a carrier pilot to be transmitted with GMSK signal in band. Our study demonstrates that for a given application over fast Rayleigh fading channel, the modem's irreducible error rate is reduced to $P_e = 5.5 \times 10^{-5}$ which is more than one order of magnitude lower than that of differential detection.

2. BBC coded GMSK modem with in-band pilot.

GMSK is traditionally viewed as a nonlinear digital FM signal with Gaussian pre-modulation lowpass filtering (see Fig. 1). TTIB is a well-known carrier pilot insertion scheme with potential application to GMSK, however, its sophistication may not be warranted in some applications. The TCT technique is more straightforward, but it is not immediately obvious how the technique can be applied to non-linear modulations.

Fortunately, Laurent [12] described a method that allows some digital phase modulations to be constructed by superposition of amplitude modulated

pulses $p(t)$ in quadrature. In this paper, we apply Laurent's method to GMSK, and construct the signal as an offset quadrature amplitude modulation. This alternative view of GMSK suggests a convenient way to insert an in-band carrier pilot. We accomplish this by applying BBC line code and highpass filtering to the I/Q channel data for the creation of a spectral void zone at the carrier frequency.

The block diagram of the proposed modem is shown in Fig.3. The binary input data $\{b_k\}$ is split into I and Q channel streams with the latter delayed by $T_s/2$. $T_s = 2T(M-1)/M$ where T is the input data bit duration. The I/Q channel data are convolved with the signaling pulse $p(t)$ before mixing with the quadrature carriers to form the GMSK signal. The waveforms $p(t)$ corresponding to several BT values are shown in Figure 2. They are smooth functions with limited time duration, and their pulse width decreases with increasing BT value. In the limiting case where BT approach infinity, $p(t)$ becomes a sine pulse that corresponds to MSK.

To facilitate carrier pilot insertion, both I/Q channel data are encoded by the Binary Block Code (BBC) [13] coder. BBC suppresses the signal's low frequency spectral component by restraining its running digital sum to be within bound. This code has simple codec structure, and low redundancy requirement. Its power spectrum $S_u(f; t)$ is given by [13]:

$$TS_u(f; T) = 1 - \left(\frac{\sin(M\omega T/2)}{M \sin(\omega T/2)} \right)^2 F(\omega T; M).$$

$$F(\omega T; M) = 0.645 \cos(M\omega T) - \frac{0.88}{M} \cos(2M\omega T) \\ - 0.85 \frac{\cos(2M\omega T) - 0.2}{\cos(2M\omega T) - 2.6} - \frac{1}{13 + 12\cos(2M\omega T)} \\ \times \left[\frac{2}{M} [-7.2 + 6.4\cos(M\omega T) - 10.8\cos(2M\omega T) + 0.6\cos(3M\omega T)] \right. \\ \left. + 0.05 [12\cos(4M\omega T) + 2\cos(5M\omega T) + 18\cos(6M\omega T) + 3\cos(7M\omega T)] \right]$$

M odd and ω is frequency in rad/s.

Figure 4 shows $S_u(f;t)$ for $M=3, 7$ and 11 where $1/(M-1)$ is the code's redundancy. In this study, the BBC code with $M=11$ is used. While it has a reasonable spectral gap (see Fig 4), this code only requires a 10 % redundancy. The highpass filter (with cutoff frequency f_H Hz) further limits the interaction between data and carrier pilot signal.

The received signal $S(t)$ is filtered by the receive BPF with bandwidth equal to the bit-rate. The carrier pilot is recovered by the pilot BPF whose bandwidth f_B is set to be $f_B=f_H$. After appropriate conditioning, the recovered pilot coherently demodulates the received signal.

3. Performance in fast Rayleigh fading channel.

As an illustrative example, the performance of a 16kb/s GMSK modem with $BT=0.25$ and $M=11$ BBC coding in a fast Rayleigh fading environment is studied using computer simulation. The Rayleigh fading process is generated using the model described in [2].

(a) Power spectrum considerations.

Figure 5a. shows the normalized spectrum of the transmit signal where the carrier pilot power level is 10 dB below the data signal. Here f_c is the carrier frequency and $f_s=1/T_s$. This spectrum features a spectral

void zone of 800 Hz that has been carved out by the $f_H=400$ Hz ideal HPF and $M=11$ BBC coder. Figure 5b shows the spectrum of the same signal when fast Rayleigh fading with Doppler frequency $f_D = 100$ Hz is introduced. Both the pilot and data signal are seen to suffer spectral spreading as a result of fast fading. In this case though, the carrier pilot is still distinguishable from data signal, and it can be recovered with a suitable bandpass filter. Figure 5c shows the spectrum when the spectral void zone is only 400 Hz. Here, the carrier pilot merges with the data signal and carrier recovery would be difficult.

(b) BER Performance.

BER performance of the modem in a fast Rayleigh fading environment with $f_D = 100$ Hz is shown in Figure 6. Curve (a) plots the performance when the pilot BPF bandwidth is $f_B=300$ Hz. Curve (b) shows the performance with $f_B=400$ Hz. The two curves crossover at approximately $C/N = 28$ dB. Below this crossover point, the modem with $f_B=400$ Hz has a slightly inferior performance. But above the crossover, the system with $f_B=400$ Hz clearly performs better. This behavior can be explained as followed. When C/N is small, channel noise dominates the contributions to the phase jitter in the recovered pilot. The modem with $f_B=400$ Hz admits more noise and hence causes more error. However, when C/N is large, the modem performance is largely determined by how accurately the recovered pilot tracks the channel fading characteristics. Here, the $f_B=400$ Hz BPF recovers more completely the fading pilot's spectral contents, and

it brings about a lower bit error rate and a lower error floor ($P_e=5.5 \times 10^{-5}$ Vs. $P_e=2.9 \times 10^{-4}$). Of course, one needs to exercise caution in employing too large a pilot recovery BPF bandwidth. Firstly, it admits more noise, but more importantly, it demands a higher cutoff frequency in the HPF of the transmitter. This introduces more ISI and performance degradation.

For comparison, we also plot the performance of a BT=0.25 GMSK modem with 2T differential detection as curve (c). The Doppler frequency is the same at $f_D = 100$ Hz. Comparison between curves (b) and (c) demonstrates the advantage of pilot-aided coherent demodulation. For small C/N (<20dB), the coherent modem is about 2 dB better than differential detection. But more importantly, the coherent modem has an error floor of $P_e=5.5 \times 10^{-5}$ which is more than one order of magnitude below that of the differential detection at $P_e=1.5 \times 10^{-3}$.

Figure 7 plots the modem's error floor against the pilot recovery BPF's bandwidth f_B , with $f_D=100$ Hz. The error floor is found to be a concave function, and it reaches its minimum at $f_B=400$ Hz.

(c) Effect of channel nonlinearity.

Figure 8 shows the effect of channel nonlinearity on the signal spectrum in a fast Rayleigh fading environment. The nonlinear characteristics is:

$$s_o(t) = s_i(t) / (1 + 0.414 * |s_i(t)|)$$

where $s_i(t)$ and $s_o(t)$ are the input and output signal respectively [11]. The Doppler frequency is $f_D=100$ Hz and

$f_B=400$ Hz. Comparison with Fig.5b indicates the presence of further spectral spreading. This is caused by the non-constant signal envelope resulting from the inserted pilot. However, the degree of spreading in this case is only minor.

4. Conclusion.

A scheme to insert carrier pilot to GMSK using BBC coding and highpass filter for coherent demodulation is proposed. As an illustrative example, the scheme is applied to a 16Kbps BT=0.25 GMSK signal over a fast Rayleigh fading channel with $f_D=100$ Hz, and its performance is investigated. The modem is found to have an error floor of $P_e=5.5 \times 10^{-5}$ which is more than one order of magnitude lower than that of differential detection. The effect of the pilot recovery BPF on modem performance is also investigated. The optimum bandwidth is found to be $f_B=400$ Hz when the Doppler frequency is 100Hz. Finally, the effect of channel nonlinearity on the signal spectrum is also investigated. With the pilot power 10dB below signal, the amount of spectral spreading is found to be minor for a certain channel nonlinearity.

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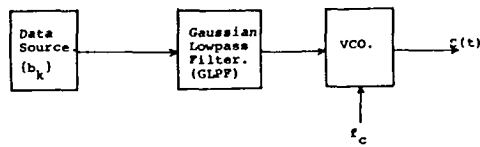


Figure 1. Conceptual generation of GMSK signal.

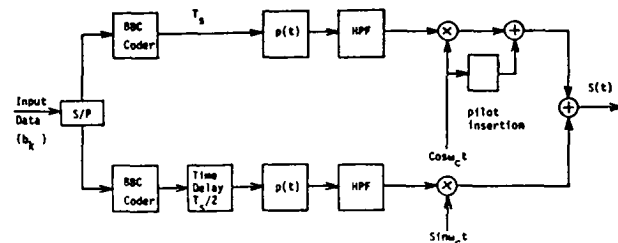


Figure 3a. Transmitter of the GMSK modem with carrier pilot insertion.

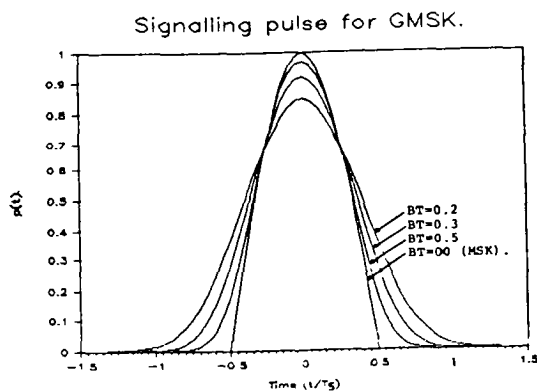


Figure 2. Signalling pulse $p(t)$ for GMSK.

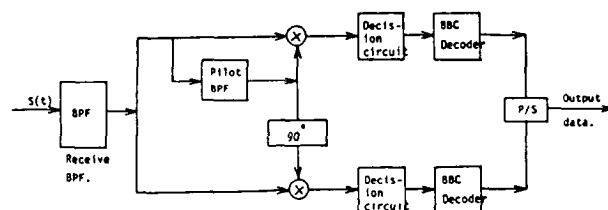


Figure 3b. Coherent detector of the coded GMSK modem.

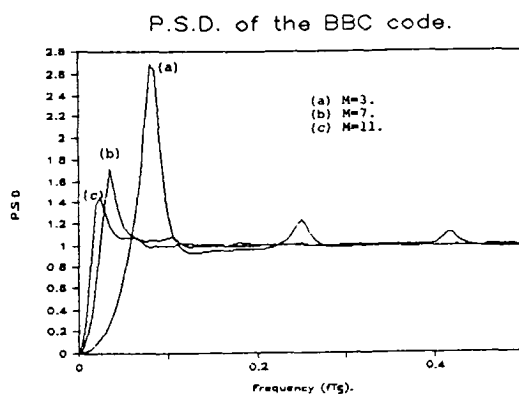


Figure 4. Power spectral density of BBC codes.

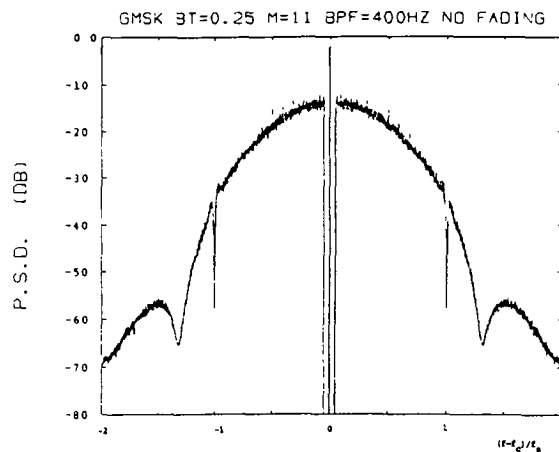


Figure 5a. Spectrum of $M=11$ BBC coded GMSK signal with pilot. $f_0 = 400$ Hz. No fading.

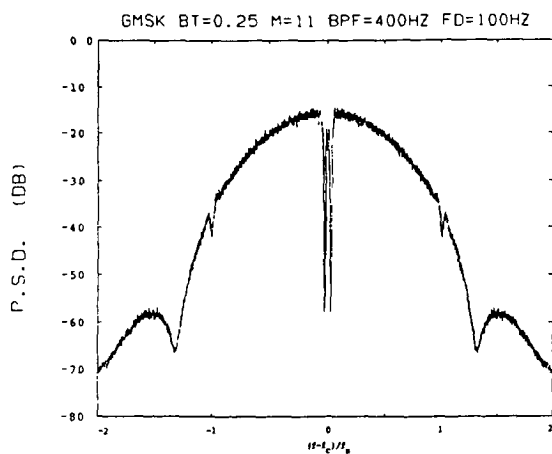


Figure 5b. Spectrum of M = 11 BBC coded GMSK signal with pilot $f_b = 400$ Hz. Fading channel with $f_D = 100$ Hz

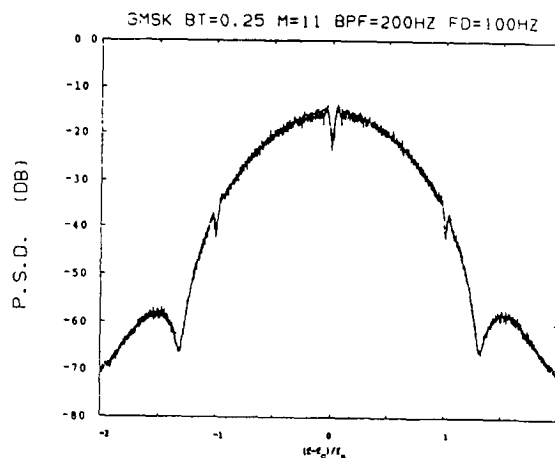


Figure 5c. Spectrum of M = 11 BBC coded GMSK signal with pilot $f_b = 200$ Hz. Fading channel with $f_D = 100$ Hz

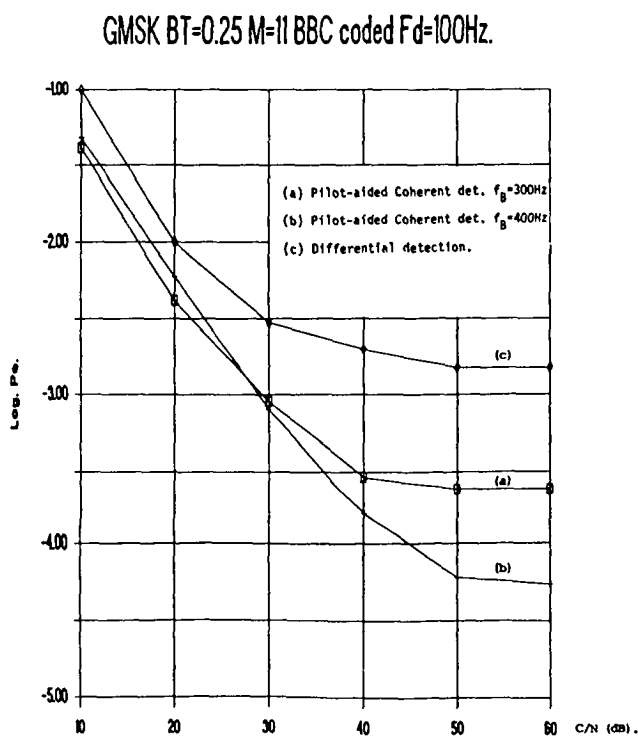


Figure 6. Performance of M = 11 BBC coded GMSK modem in fast Rayleigh fading channel. 16 kb/s. BT = 0.25. Doppler frequency $f_D = 100$ Hz. Receive BPF bandwidth = bit rate.

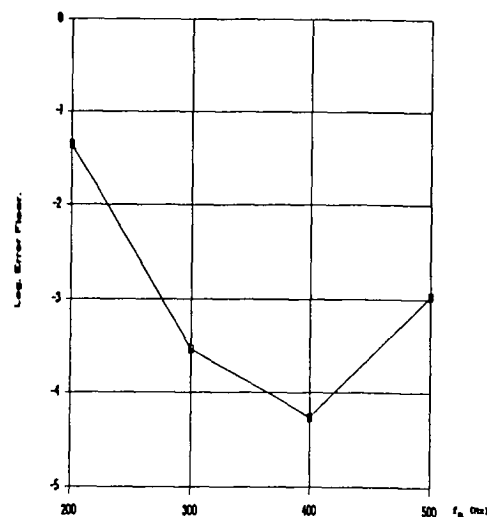


Figure 7. Error floor of M = 11 BBC coded GMSK signal vs pilot recovery BPF bandwidth.

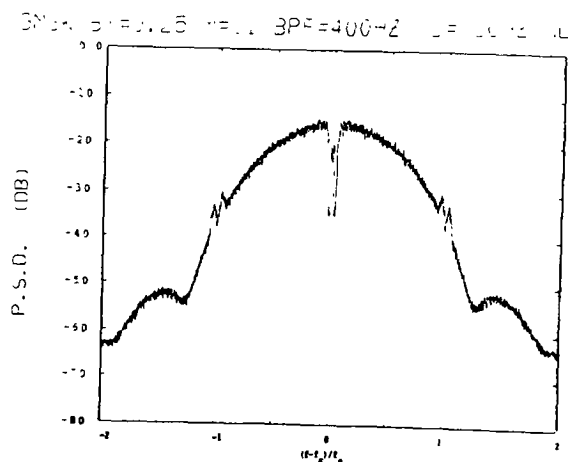


Figure 8. Spectrum of M = 11 BBC coded GMSK signal with pilot $f_b = 400$ Hz. Nonlinear channel with $f_D = 100$ Hz